Preliminary test of the prototype modular cryostat for a 10 MW offshore superconducting wind turbine

J. Sun, R. Ramalingam, S. Santiago, H. Neumann
Contents

1. Introduction
   - Motivation
   - SUPRAPOWER project

2. Experiment Setup
   - Modular cryostat introduction
   - Assembly and instrumentation

3. Results and discussion
   - Temperature during cooling down
   - Comparison with simulation
   - Heat load estimation

4. Outlook and summary
## Offshore Wind

### Market Perspectives

<table>
<thead>
<tr>
<th></th>
<th>2020</th>
<th>2030</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Europe</strong></td>
<td>40 GW</td>
<td>150 GW</td>
<td>460 GW</td>
</tr>
<tr>
<td><strong>World</strong></td>
<td>100 GW</td>
<td>375 GW</td>
<td>1150 GW</td>
</tr>
<tr>
<td><strong>Cost per MW</strong></td>
<td>4,5 M€</td>
<td>3,5 M€</td>
<td>2,5 M€</td>
</tr>
</tbody>
</table>

### Additional Data

<table>
<thead>
<tr>
<th></th>
<th>2020</th>
<th>2030</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Europe</strong></td>
<td>180,000 M€</td>
<td>565,000 M€</td>
<td>1.34 B€</td>
</tr>
<tr>
<td><strong>World</strong></td>
<td>450,000 M€</td>
<td>1.412 B€</td>
<td>3.35 B€</td>
</tr>
</tbody>
</table>

*Source: EWEA and IEA*

1M€ = 10^6€
1B€ = 10^12€

**Huge offshore wind market is expected for the upcoming years. Cost reductions are highly required to reach these predictions.**
Wind Turbine Dimension

Offshore wind power market shows the tendency of large-scale wind turbines

Source: Siemens & Gamesa at Bilbao Marine Energy Week, 2015
**Large-scale superconducting wind turbine**

- **Superconductivity** maybe the only technology to scale up offshore wind turbine to 10 MW and beyond

<table>
<thead>
<tr>
<th>INNWIND (EU)</th>
<th>suprapower</th>
<th>ecoswing</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 years</td>
<td>2012-2016</td>
<td>2015-2019</td>
</tr>
</tbody>
</table>

- DTU
- TU Delft
- SINTEF
- SIEMENS
- DNV·GL
- tecnalia
- KIT
- Columbus Superconductors
- öerlikon leybold vacuum
- Envision
- UNIVERSITY OF TWENTE.
- THEVA
- ECO
- Fraunhofer
- DNV·GL
- Delta Energy Systems
- JE
- Jeumont Electric
- Cryogenics Group
Suprapower aims to

- develop a new concept of **innovative, lightweight, robust and reliable 10 MW** class SC wind turbine for offshore applications

**Objective:** 30% weight and size reduction

- Modular concept
  - Validation of generator concept through a **scale machine**
Contents

1. Introduction
   - Motivation
   - SUPRAPOWER project

2. Experiment Setup
   - Modular cryostat introduction
   - Assembly and instrumentation

3. Results and discussion
   - Temperature during cooling down
   - Comparison with simulation
   - Heat load estimation

4. Outlook and summary
Cooling system - Modular concept

Source: TECNALIA

Modular cryostat are proposed to ease installation and maintenance
Modular cryostat for validation - Explosive view

- Vacuum vessel
- Window cover
- Cryocooler Cold head
- Active cooled shield
- Dummy coil
- Assemble tools
- Support
Active cooled shield made of copper links to the cryocooler 1\textsuperscript{st} stage
Superconducting (dummy) coil links to the cryocooler 2\textsuperscript{nd} stage
Flexible copper thermal anchor are adopted to reduce thermal contraction
4 groups of Ti-6Al-4V supporting rods are placed as supporting structure
Each group include 8 rods per coil support and 8 rods per shield support
Symmetrical structure are applied on account of rotating cryostat
Experiment setup

- Dummy coil
- Active cooled shield
- Instrumentation
- Vacuum vessel
6 calibrated TVO temperature sensors with 1% uncertainty were installed.

No temperature sensors were installed on the active cooled shield, and no heaters were performed.
Temperature sensors installation

Cryocooler
Cold head

Active cooled shield
Vacuum vessel

1st stage

2nd stage

Thermal anchor
Dummy coil
Final experiment setup
Contents

1. Introduction
   - Motivation
   - SUPRAPOWER project

2. Experiment Setup
   - Modular cryostat introduction
   - Assembly and instrumentation

3. Results and discussion
   - Temperature during cooling down
   - Comparison with simulation
   - Heat load estimation

4. Outlook and summary
It took about **20 hours** for the first stage thermal anchor to reach the lowest temperature, which is around **33 K**

- The second stage thermal anchor together with the linked dummy coil required **56.5 hours** to reach the lowest temperature, which was around **9.8 K and 9 K** respectively.

Experiment results – Cooling down
The temperature vibrates in a certain range, which is around 0.5 K for the dummy coil and 0.4 K for the second stage thermal anchor.

The instability of temperature is ascribed to the cryocooler cold head. The motion of the displacer of the GM cryocooler produces a periodic temperature vibration.
Cooling down simulation – Cryocooler load map

\[
\frac{d}{dt} (\rho V c_p T)_S = Q_H - Q_L - Q_{A_1}
\]
\[
\frac{d}{dt} (\rho V c_p T)_{SC} = Q_L - Q_{A_2}
\]
\[
\frac{d}{dt} (\rho V c_p T)_{A_1} = Q_{A_1} - Q_{C_1}
\]
\[
\frac{d}{dt} (\rho V c_p T)_{A_2} = Q_{A_2} - Q_{C_2}
\]
\[
Q_H = Q_{s_1} + Q_{r_1} + Q_{v_1}
\]
\[
Q_L = Q_{s_2} + Q_{r_2} + Q_{v_2}
\]

\[
Q_s = N \frac{A}{L} \int_{T_L}^{T_H} k(T) \, dT
\]

\[
Q_r \approx \frac{\sigma (T_H^4 - T_L^4)}{\varepsilon_H A_H} + \frac{1}{A_L} \left( \frac{1}{\varepsilon_L} + \frac{2N}{\varepsilon_N} - N \right)
\]
Simulated lowest temperatures are nearly the same with the experiment results.
The trends of simulated cooling down curve agree with the experiment results.
The experiment requires more time for the coil to reach the lowest temperature.
The exceed time is around 7.5 hours.
Following the mentioned approximation, the 1st stage and 2nd stage of the cryocooler reaches a temperature of 33 K and 9 K, respectively.

Then based on the load map, the estimated heat loads to the cryocooler are 25 W and 2.5 W at 1st stage and 2nd stage, respectively.

\[
\frac{m_{sc} c_p}{dT_{sc}} = Q
\]

\[
c_p = \frac{\int_{T_l}^{T_h} c_p dT}{T_h - T_l} = 1.0955 \frac{J}{(kg \cdot K)}
\]

The calculated heat load based on Equation above is 1.62 W.
Contents

1. Introduction
   - Motivation
   - SUPRAPOWER project

2. Experiment Setup
   - Modular cryostat introduction
   - Assembly and instrumentation

3. Results and discussion
   - Temperature during cooling down
   - Comparison with simulation
   - Heat load estimation

4. Outlook and summary
Summary

- A modular cryostat for 10 MW wind turbine was designed, manufactured and assembled for validation within the SUPRPOWER project.

- Numerical simulation of the cooling down for the modular cryostat was performed and agreed with the experimental results.

- The modular cryostat was preliminary tested experimentally. The dummy coil and thermal shield could reach a lowest temperature of 9 K and 33 K, respectively.

- Full measurement will be performed in the next step.
Thanks for your interest

More info at
www.suprapower-fp7.eu

Jiuce Sun
Institute for Technical Physics
Karlsruhe Institute of Technology (KIT)
Jiuce.sun@kit.edu

Holger Neumann
Institute for Technical Physics
Karlsruhe Institute of Technology (KIT)
Holger.neumann@kit.edu